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# SIMPLIFIED EVALUATION FOR THE SERA-TA BLIND PREDICTION: SEISMIC BEHAVIOR OF MASONRY CROSS VAULTS

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## Abstract

*Experimental tests performed on prototypes provide important information to improve the knowledge under dynamic actions. Masonry vaults play a much relevant role in the seismic response of heritage masonry buildings and their behavior is very hard to predict due to the strong variability and heterogeneity of the physical and mechanical and input parameters. Since it is not possible to perform initial blind calibrations, the development of simplified models able to capture the main aspects is certainly a useful tool to plan experimental tests. In this specific case, the development of a model able to provide the following outputs has been the main goal: the threshold at which evident damage is expected; identify the areas where the damage is concentrated; identify the type of damage.*

*The masonry cross vault has been modelled by means of non-linear shell elements both for unreinforced and strengthened configuration. Managing simple models allowed also performing some consecutive time histories including the effects of previous signals, as tested prototype was subjected to replicas. The results obtained by the FE model have been compared with the experimental results. The simplified approach discussed in this paper represents a useful support tool to design dynamic tests on full-scale or scaled masonry structures.*

**Keywords:** Dynamics of concrete and masonry structures, Numerical simulation methods for dynamic problems, Reliability of dynamic systems.

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# 1 INTRODUCTION

The planning of experimental programs both for single elements [1] and for scaled structures [2, 3] is a very critical phase. It increases when the goal focuses on masonry scaled buildings subjected to dynamic actions. Since it is not possible to make numerical calibrations before the test [4], the development of simplified models able to fix the main aspects represents a useful tool to set up experimental tests. In this case, simplified numerical modelling able to estimate the threshold at which evident damage is expected, the areas where the damage is concentrated, the type of damage and the expected maximum displacement values was developed. The data initially provided in terms of elastic and mechanical properties of the materials were adopted as main input for the development of the numerical model. The physical and mechanical properties have been assigned starting from tests performed on similar masonries [5]. In fact, in an initial blind phase, the level of knowledge is very low and the numerical model must be compatible with it [6, 7]. Excessively refined models are often more sensitive to input parameters and the cannot be used at initial phases [8, 9]. The main goal of the experimental program was to investigate the behavior of brick masonry cross vaults under different seismic inputs, in terms of damage, displacement capacity and peak acceleration [10].

# 2 STRUCTURAL ANALYSIS

Authors preferred a simplified approach, with some further very simple assumptions mainly due to original time constraints and initial knowledge level; the time extension did not allow to use a more refined approach (eventually a different more refined FEM code, also in use in our research group), but allowed to perform some consecutive time histories including the effects of previous signals.

In particular, since it is not possible to perform initial calibrations, the development of simplified models able to capture the main aspects is certainly a useful tool to plan experimental tests [11]. In this specific case, the development of a model able to provide the following output has been the main goal:

- The threshold at which evident damage is expected;
- Identify the areas where the damage is concentrated;
- Identify the type of damage.

Such simplified model has been successfully used before for similar problems of masonry structures and components modeling [12-18]. The masonry structure has been modelled by means of non-linear shell elements in SAP2000 (developed by “Computers and Structures”). A perspective view of numerical model is shown in the figure 1.

The real scale masonry specimen is made of a main cross vault modelled by means of non-linear shell elements. The boundary conditions reproduce the experimental setup made of steel elements, some are fixed, while others are able to slide only in horizontal direction, while steel bars reproduce their mutual connections.

The masonry stress-strain constitutive relationship must be compatible with a simplified approach. The masonry has been modelled as elastic perfectly plastic in compression. The maximum value of the compressive stress is always lower than the compressive strength for all time histories [19].

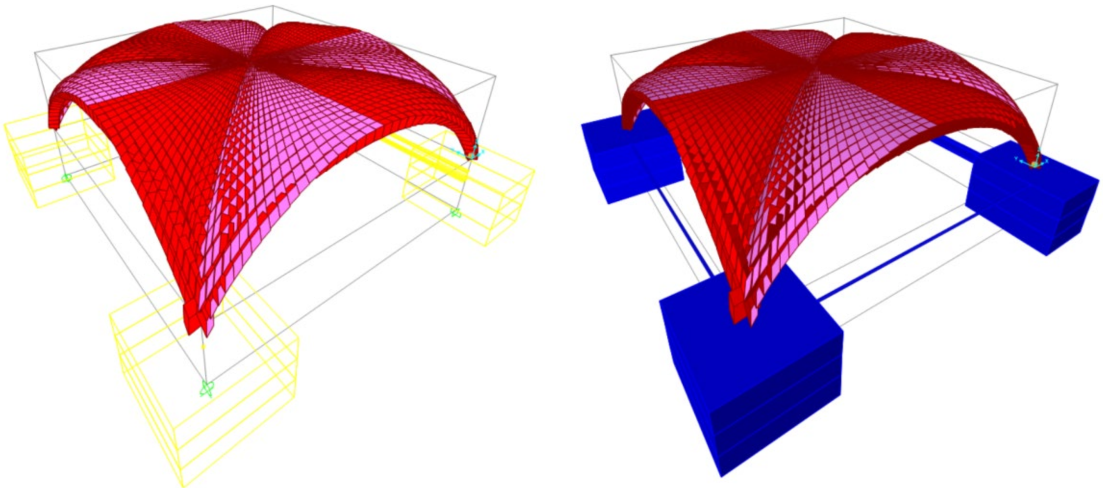
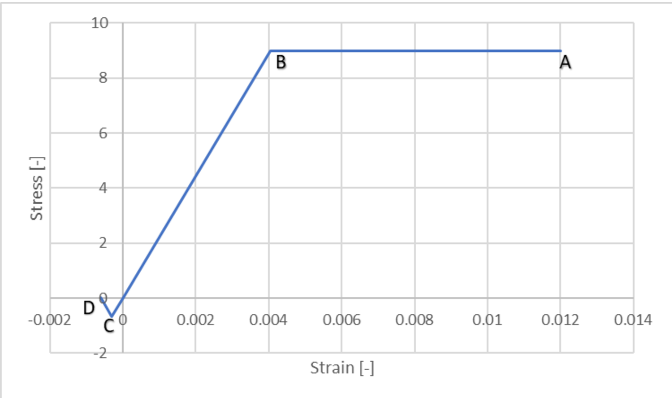


Figure 1: Numerical model: three dimensional views.

For this reason, no further improvement of the compressive behaviour was performed. The masonry behaviour in tension has been modelled limiting the maximum tensile strain of masonry at $3\times\varepsilon_T$, where $\varepsilon_T$ represents the cracking (peak) strain of the masonry in tension. The tensile behaviour is certainly the most critical, and it was assumed a reduced fracture energy based on preliminary information and this was confirmed after the dynamic tests [20, 21].

Figure 2 shows the nonlinear stress-strain constitutive relationship used for masonry, modelled with quadrilateral shell finite elements.




| Point | Strain [-] | Stress [MPa] |
|---|---|---|
| ***A*** | 0.012 | 9.0 |
| ***B*** | 0.00405 | 9.0 |
| ***0*** | 0 | 0 |
| ***C*** | 0.0003 | -0.66 |
| ***D*** | 0.00059 | 0 |

Figure 2: Stress-strain constitutive relationship for masonry.

Parameter for viscous model has been fixed equal to 5% for all time history analyses as shown in many tests performed on similar masonry [22, 23].

The numerical model was subjected to a sequence of dynamic signals at the base. The accelerograms refer to the desired signal. However, the experimental practice has shown that the desired signals are always affected by an alteration due to many disturbing factors. It has been seen that the experimental variations from the desired signal do not negligibly affect the numerical results. However, this statement is subordinate to the goals of this study which are aimed at a simplified analysis of the structure. Therefore, the theoretical signals were considered to assess the capacity of the masonry cross vault.

## 2.1 Dynamical behavior

A modal analysis was performed to assess the dynamical behavior of masonry vault. The vault shows a prevalently torsional behavior as shown in the following figures. This aspect is probably due to the non-symmetric restraint conditions of specimen [24, 25].

The boundary conditions reproduce the setup; some steel blocks are fixed, while others can slide only in some directions, and finally there are steel bars constraining their relative displacements, modelled as trusses.

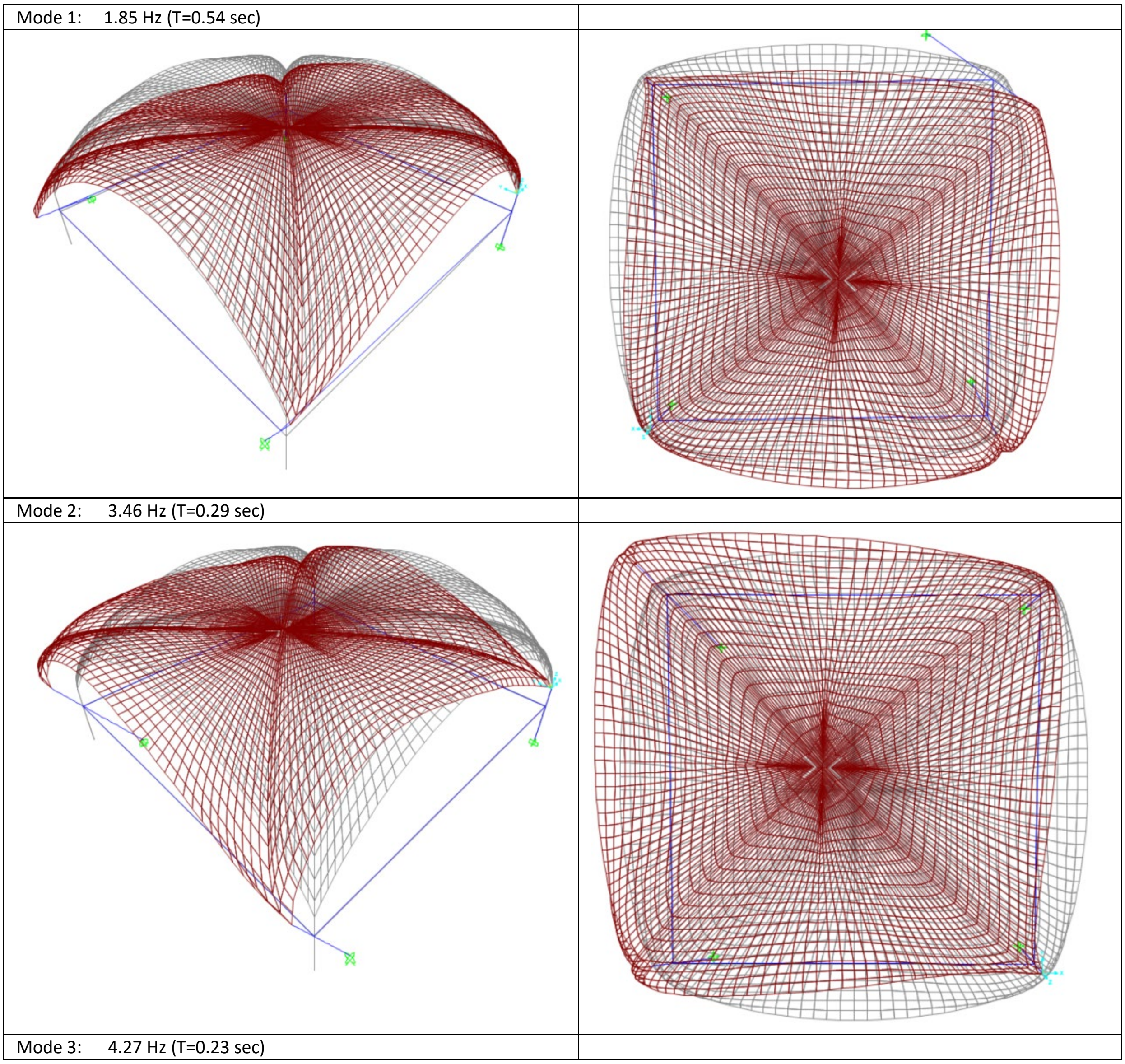



Figure 3: Main modal shapes, prospective view and top view, in the left and right column respectively.

A time history analysis was performed to assess the structural behavior of the real scale masonry vault. The time histories were assigned like as sequential analyses. In particular, in the output of sequential shaking analyses, the residual displacements of the previous shakings have been subtracted, for representation only, but from a mechanical point of view, residual displacements were found at the end of previous shakings and affect the numerical modelling.

## 2.2 Numerical results and experimental comparison

The adopted numerical approaches do not allow to plot a failure mechanism. However, a probable failure mechanism and the linked crack pattern can be identified starting from the internal stresses configuration, by means of Engineering judgment. In particular, for several steps of the time history, the principal stresses are shown in the following figures.

The torsional behavior/in-plane shear is the most significant mechanism. In main load direction the aligned longitudinal arches have the typical failure mode with longitudinal arch behavior (cracks at keystone and springers) according to the plotted stress contour maps. This is more evident in the opposite arches at the two sides (yellow rectangles, of figure 4). Torsional effects yield to cracks along the diagonal ribs of the vault, starting from Nord side (red dashed lines in figure 4).

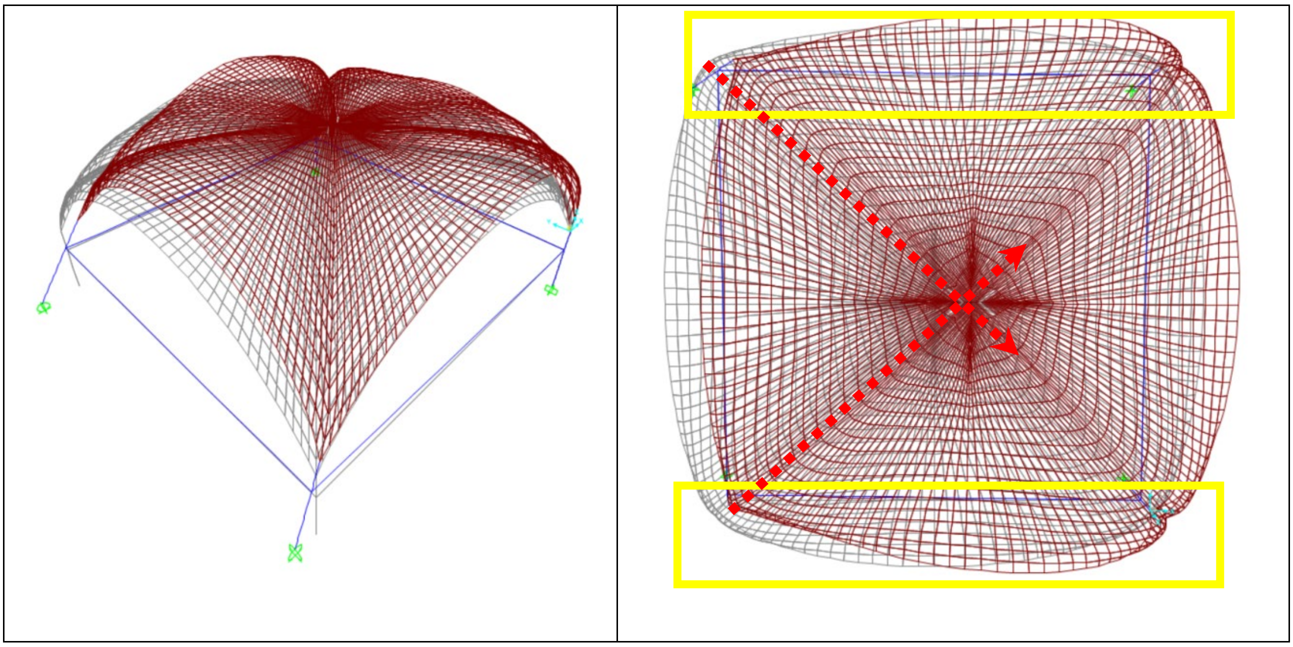
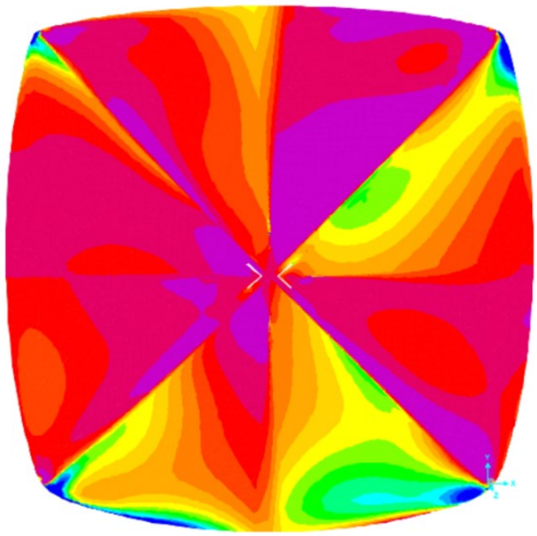
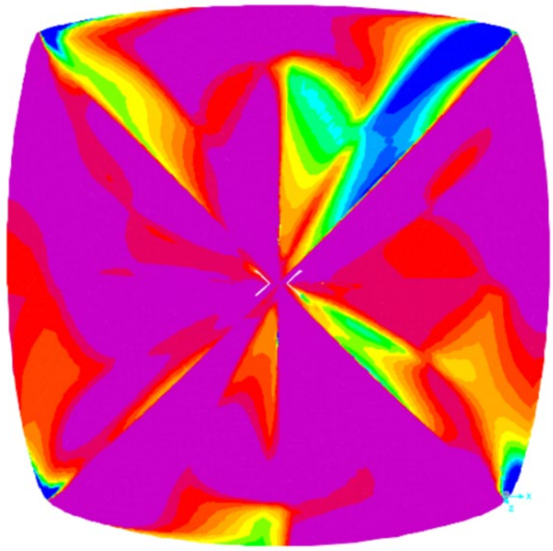


Figure 4: Torsional effects yield to cracks along the diagonal ribs of the vault.

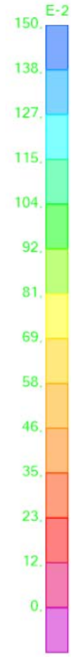
The results in terms of internal principal stresses were shown in figures 5. In particular, the localization of the principal tensile stresses both at the intrados (blue areas of figure 5 a, c and e) and at the extrados (figure 5 b, d and f) was shown with reference to several steps of the last dynamic signal.

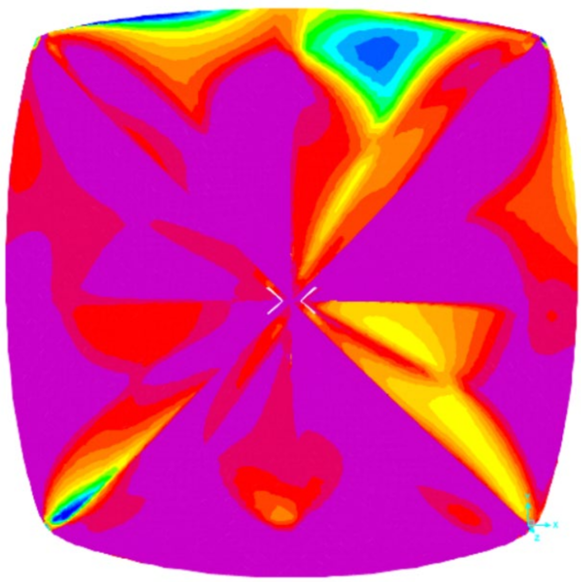


a)
Localization of the principal tensile stresses (blue areas intrados), timestep 3.905 sec

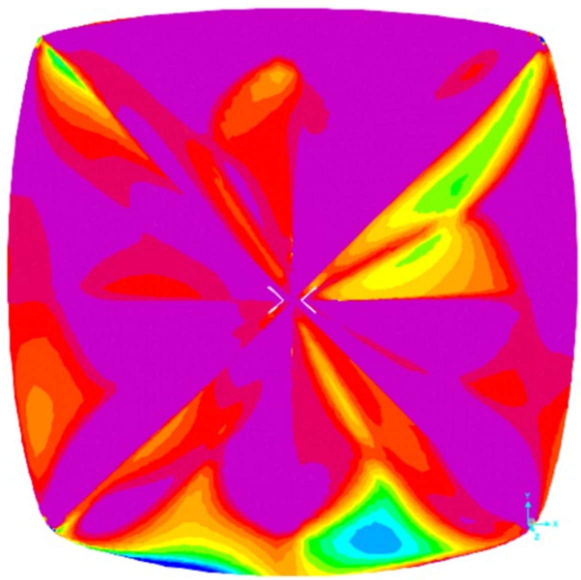


b)
Localization of the principal tensile stresses (blue areas extrados), timestep 3.905 sec

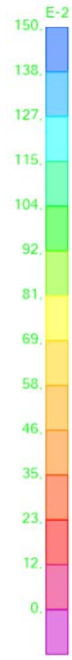


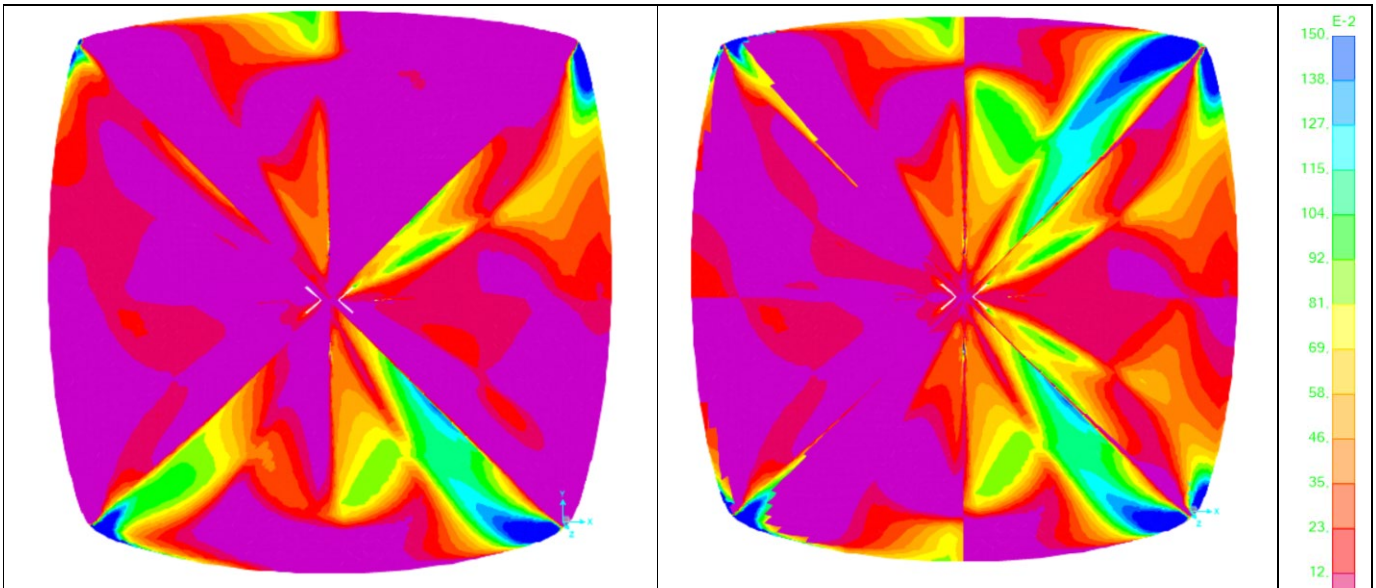



c)
Localization of the principal tensile stresses (blue areas intrados), timestep 4.415 sec



d)
Localization of the principal tensile stresses (blue areas extrados), timestep 4.415 sec



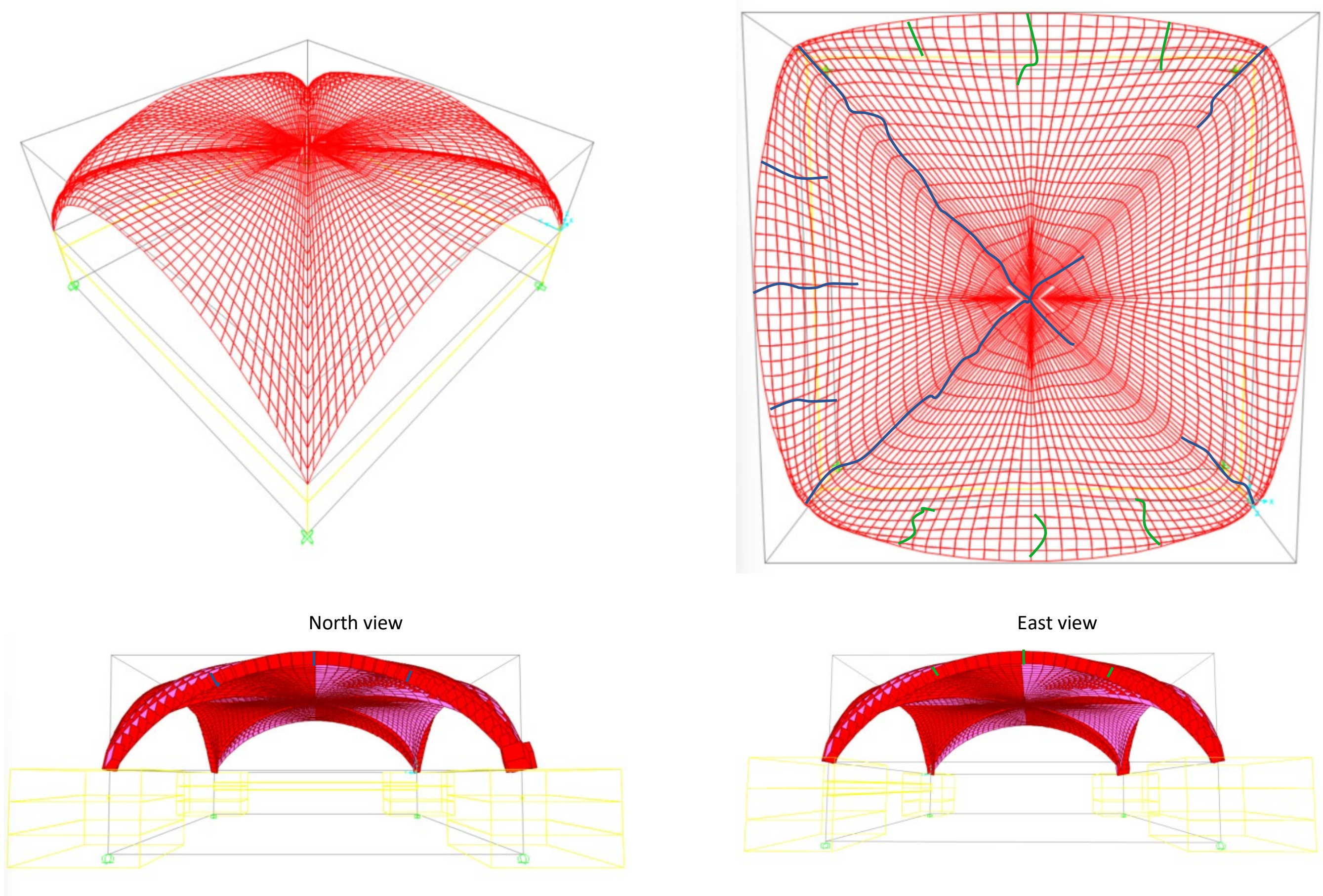



e)
Localization of the principal tensile stresses (blue areas intrados), timestep 4.25 sec

g)
Localization of the principal tensile stresses (blue areas extrados), timestep 4.25 sec

Figure 5: Simulated internal principal stresses (contour map in MPa).

The internal stresses provide important information about the identification of an expected crack pattern as shown in figure 6.



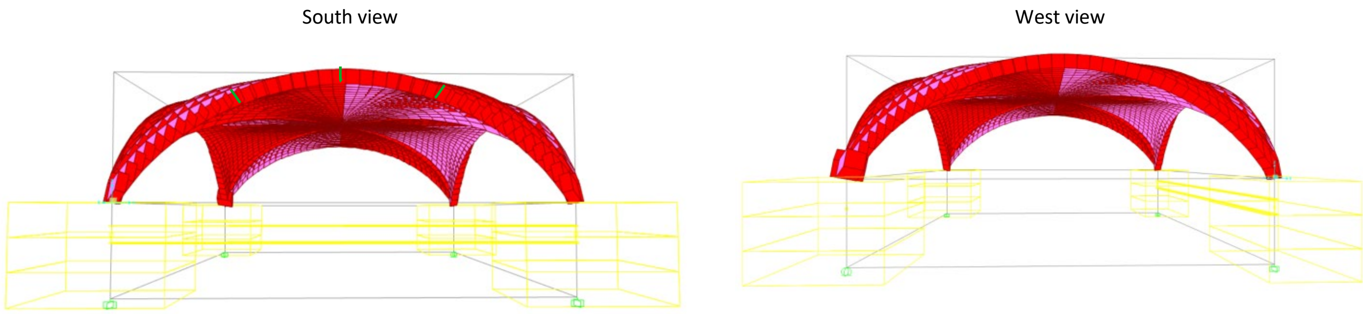



Figure 6: Simulated crack patterns.

## 3 CONCLUSIONS

The main goal of this work was to develop a simplified model compatible with preliminary analysis. Many experimental programs are planned on the basis of assumptions and choices which are subsequently amended. This is a very key issue, especially for masonry structures subjected to dynamic actions. A model able of simulating the main information on structural behavior is a useful tool, especially in the planning phase of experimental programs. The numerical model was in fact developed on the basis of initially available mechanical properties. Therefore, the numerical model was developed to test the reliability of a simplified approach (pre diction [9]) and not to accurately model the behavior of the tested masonry vault (post diction [26]). A reliable model is necessarily calibrated on the basis of deeper data from experimental tests. However, such refined calibration would make the simulations highly sensitive to the peculiarities of the case study, while this simplified modelling and approach would provide a more general outcome.

The approach is unable to accurately predict internal redistribution once evident damage has been achieved. It is obviously necessary to develop more refined models. They can be developed after specific numerical calibrations should be used.

From the point of view of damage, the developed numerical model was satisfactory. Main damage pattern was satisfactorily identified in accordance with the location, load threshold and typology experimentally found.

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